The morphological mix of field galaxies to $m_I = 24.25$ mag ($b_J \sim 26$ mag) from a deep HST[1] WFPC2 image

Simon P. Driver, Rogier A. Windhorst, Eric J. Ostrander,

Department of Physics and Astronomy, Arizona State University,

Box 871504, Tempe, AZ 85287-1504

William C. Keel,

Department of Physics and Astronomy, University of Alabama,

Box 870324, Tuscaloosa, AL 35487-0324

Richard E. Griffiths and Kavan U. Ratnatunga,

Bloomberg Center for Physics and Astronomy, The Johns Hopkins University,

Box 182695, Baltimore, MD 21218-2695

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ABSTRACT

We determine the morphological mix of field galaxies down to $m_I \simeq 24.25$ mag ($m_B \sim 26.0$ mag) from a single ultradeep HST WFPC2 image in both the V_{606} and I_{814} filters. In total, we find 227 objects with $m_I \leq 24.5$ mag and classify these into three types: ellipticals (16%), early-type spirals (37%) and late-type spirals/Irregulars (47%). The differential number counts for each type are compared to simple models in a standard flat cosmology. We find that both the elliptical and early-type spiral number counts are well described by *little or no*-evolution models, but only when normalized at $b_J = 18.0$ mag. Given the uncertainties in the luminosity function (LF) normalization, both populations are consistent with a mild evolutionary scenario based on a normal/low rate of star-formation. This constrains the end of the last *major* star-formation epoch in the giant galaxy populations to $z \geq 0.8$.

Conversely, the density of the observed late-type/Irregular population is found to be a factor of 10 in excess of the conventional no-evolution model. This large population might be explained by either a modified *local* dwarf-rich LF, and/or strong evolution acting on the *local* LF. For the dwarf-rich case, a *steep* faint-end Schechter-slope ($\alpha \simeq -1.8$) is required plus a five-fold increase in the dwarf normalization. For a purely evolving model based on a *flat* Loveday *et al.* (1992) LF ($\alpha \simeq -1.0$), a ubiquitous starburst of $\Delta I \sim$2.0 mag is needed at z$\simeq$ 0.5 for the *entire* late-type population. We argue for a combination of these possibilities, and show that for a steep Marzke *et al.* (1994) LF ($\alpha \simeq -1.5$), a starburst of $\sim$ 1.3 mag is required at z $\simeq$ 0.5 in the entire late-type population, or $\sim$ 2.0 mag in $\sim$20% of the population.

Subject headings: galaxies: elliptical — galaxies: spiral — galaxies: irregular — galaxies: luminosity function — galaxies: evolution

1 INTRODUCTION

Over recent years the nature of faint blue field galaxies observed in deep CCD images has been addressed through two main techniques: galaxy number counts and faint redshift surveys (Koo & Kron 1992, KK92). While differential galaxy counts in short wavebands show an remarkable excess of faint blue galaxies (Kron 1982; Broadhurst, Ellis & Shanks 1988, BES), the current faint redshift surveys show a distribution which is well fit by the standard no-evolution model (although the

LF normalization is incorrect). This conundrum has given rise to a large number of sophisticated models, most of which introduce an evolutionary process (see Phillipps & Driver 1995, for example, and references therein).

Recent papers from the HST Medium Deep Survey (MDS) have now introduced an additional constraint: the *morphological* classification of faint field galaxies at HST's resolution of $0.1''$ FWHM. Casertano *et al.* (1995, CRGINOW) give the differential galaxy number counts for HST bulges and disks separately from the pre-refurbished WF/PC MDS database (13,500 galaxies with $m_{I_{F785LP}} <$ 21 mag. Griffiths *et al.* (1994), Driver, Windhorst & Griffiths (1995, DWG) and Glazebrook *et al.* (1995a, GL95a) use WFPC2 data to extend the morphological classification of faint field galaxies to $m_I \simeq 22.0$ mag. They find that about one third of the total differential number counts with $m_I \leq 22.0$ mag consist of Sd/Irregular galaxies, far more than expected based on estimates of the local Sd/Irr population. About 35% of this population shows clear signs of star-formation (c.f. DWG). The remaining contribution to the number counts at $m_I \sim 22.0$ mag consists of normal ellipticals and spirals, which are well fitted by standard mild or no-evolution models (DWG, GL95a). Here we analyze the 24-orbit WFPC2 exposure of Windhorst & Keel (1995, WK), and extend the morphological classification of faint field galaxies to $m_I \simeq 24.25$ mag ($m_B \simeq 26$ mag).

2 WFPC2 DATA REDUCTION AND IMAGE ANALYSIS

This single deep WFPC2 field has a total of 5.7 hr exposure in both V_{606} and I_{814} , and was reduced as described in WK, DWG, and CRGINOW (*i.e.* super-biases, -darks, -sky-flats, and bad-pixel maps from the MDS). Cosmic-ray removal was achieved by the technique described in Windhorst, Franklin & Neuschaefer (1994) updated for WFPC2. Figure 1 (Color Plate 1) shows a color plate of the entire WFPC2 field. The PC image was not used for the current study due to its lower surface brightness (SB) sensitivity. Initial object positions and total magnitudes were measured using an isophotal object-finding software of Ratnatunga *et al.* (1995). All objects were examined by eye and recombined or split as necessary. This yields two object catalogs in V and I which are complete, based on the turn-over of the counts, to $m_I \simeq 25.50$ and $m_V \simeq 26.75$ mag. In total, we find ~ 600 and ~ 850 objects, respectively, down to these limits in the three WFC CCD's, implying a surface density of 4.4×10^5 and 6.2×10^5 objects deg^{-2}. In this paper, we consider only those

galaxies with $m_I \leq 24.25$ mag, *i.e.* 1.25 mag above our formal completeness limit. Hence, for low SB galaxies, we become incomplete for objects with isophotal extent $\gtrsim$ 7 arcsec^2, and for luminous bulges at z$\gtrsim$ 1.0. We find no objects down to $m_I = 24.25$ mag larger than 1.0 arcsec^2 and the current faint redshift surveys — which extend to $m_{b_J} = 24$ mag — find very few galaxies with z$\gtrsim$ 1 (Glazebrook *et al.* 1995b), although these surveys may also suffer SB-selection effects. An in-depth discussion of the completeness of HST images is given by Neuschaefer *et al.* (1995).

3 HST GALAXY NUMBER COUNTS AS FUNCTION OF TYPE

Figure 2a shows the differential number counts for the HST I-band compared to ground-based data (Tyson 1988; Lilly *et al.* 1991; Driver 1994; Neuschaefer *et al.* 1995). Note the good agreement between the ground-based counts and our deep HST counts, as well as with previous HST I-band counts (DWG and the WF/PC I_{F785LP}-band counts of CRGINOW). The conversion from WFPC2 F814W to Cousins I_C is derived from Holtzman *et al.* (1995) and Bahcall *et al.* (1994) as: $I_{814} = I_C + 0.05$ mag, assuming a mean galaxy color of $(V - I)_C \simeq 1.5$ (Driver 1994) and $(V_{606} - I_{814}) \simeq 1.0$ mag (DWG). Our deep WFPC2 I-band counts extend the ground-based counts in Fig. 2a with a best fit slope of 0.34 ± 0.03 for $22.0 < m_I < 25.5$ mag. The V-band counts have a slope of 0.38 ± 0.03 for $23.0 < m_V < 27.0$ mag, implying a trend towards bluer $(V - I)$ colors at fainter magnitudes. At $m_I \simeq 21.5$ mag, the mean field galaxy $(V - I)$ color is 1.3 ± 0.3 (1σ), changing to 0.8 ± 0.3 at $m_I \simeq 25.0$ mag, and shows little correlation with galaxy type (see DWG). Hence, we do not use color to classify, moreover redshifts and K-corrections at I$\simeq$24 mag ($b_J \simeq$26) are unknown.

Following the methods in DWG, we did the photometry for the 227 objects with *total* flux $m_I \leq 24.5$ mag, resulting in an accuracy of $\pm$0.1 mags (c.f. DWG). The objects were classified into ellipticals, early-type spirals, and late-type spirals/Irregulars using both the V and I-band morphology and light-profiles. As in DWG the distinction between "early" (Sabc) and "late" (Sd/Irr) is based on a combination of their measured central SB and a careful assessment of their measured light-profiles, bulge-to-disk ratios, and grey-scale images (see DWG for an example of the Hubble sequence at $m_I \simeq 21.5$ mag). The final assigned galaxy types are the consensus of four *independent* classifiers (SPD, RAW, EJO and WCK), and were determined by averaging the number of galaxies in each class and in each magnitude interval (as opposed to defining an average

or most likely class for each object individually). The consistency between the four independent classifiers is summarized in Table 1. Note that the scatter in the interval $22.25 < m_I < 24.25$ is equivalent to that in $20.25 < m_I < 22.25$mag.

Figure 2 shows the differential number counts for: ellipticals (2b), early-type spirals (2c), and late-type spirals/Irregulars (2d). Fig. 2 also includes the WF/PC data of CRGINOW (for all galaxies, ellipticals and spirals) for $I \leq 21.0$ mag, and the WFPC2 data of DWG for $I \leq 22.0$ mag. Errors are derived from assuming Poisson statistics. The formal errors ($\sqrt{n}$) are shown by *solid* errorbars. Vertical dotted lines indicate the *total* range covered by the four independent classifiers, and are a *conservative* estimate of the true classification errors. Where our new data overlaps with that of CRGINOW and DWG, there is good agreement within the formal errors. The largest errors occur for the E/S0's, where the statistics are smallest and which are the hardest to recognize — even with HST — due to their small scale-lengths (Mutz *et al.* 1994; Windhorst *et al.* 1994a, b). The level of agreement between our four independent classifiers down to I$\leq$ 24.25 mag is comparable to that achieved by DWG for $I \leq 22.0$ mag. In Table 1, the disagreement between classifiers is exaggerated because the data is binned into a *small* number of classes. E.g., if two classifiers agree on a galaxy as S0 and two as Sa, this might be considered a reasonable agreement, but because we bin objects into three classes, such disagreements seem more significant. Table 2 shows the morphological mixes observed at various flux limits. The bright end of our HST sample agrees well with the faint end of the DWG sample, and the bright end of the DWG sample agrees well with the local fractions (Shanks *et al.* 1984).

We applied the bulge *or* disk-fitting algorithms of CRGINOW (1995) to provide an *independent* automated classification for all 227 objects into ellipticals or spirals, as shown in Table 2. While this algorithm cannot distinguish between mid and late-type spirals, the fraction of brighter galaxies ($21 \leq I < 23.0$ mag) classified into bulges and disks *by the algorithm* is 30% and 70%, respectively, while *by eye* it is 32% and 68%. At the faint end ($23 \leq I < 24.5$ mag) the correspondence is still satisfactory: the bulge and disk fractions are 21% and 79% *by the algorithm*, and 14% and 86% *by eye*, respectively. Software to achieve two-dimensional simultaneous bulge *plus* disk fits is under development, and will be described in a subsequent paper (Ratnatunga *et al.* 1995). A comprehensive spectroscopic survey is also in progress for the DWG sample (Driver *et al.* 1995, in prep.), and will help confirm these classifications.

We conclude that we have — within the limits of the available data — a consistent picture of the trend of morphological mix with apparent magnitude. Figure 2 and Table 2 show that the galaxy mix at *faint* magnitudes is significantly different from the local values, with a far higher proportion of late-type galaxies is seen at the HST limit.

4 MODEL FITTING

To model the differential number counts for each galaxy type separately, we adopted three independent luminosity functions (LF's), a standard flat cosmology ($\Lambda = 0, \Omega = 1$ and $H_o = 50$ kms$^{-1}Mpc^{-1}$, c.f. Phillipps, Davies & Disney 1990) and K-corrections (c.f. Driver *et al.* 1994). The modelling process is described in DWG. For *non-evolving* E/SO's and Sabc's, we parameterized the *observed* luminosity distributions (LD's) from Marzke *et al.* (1994b, MGHC) using their tabulated values for E/SO: $M_B^* = -20.5$ mag, $\alpha = -0.9$, $\phi_* = 1.14 \times 10^{-3}$ Mpc^{-3}, and for Sabc: $M_B^* = -20.3$ mag, $\alpha = -0.8$, $\phi_* = 1.74 \times 10^{-3}$ Mpc^{-3}. The LF's were exponentially cut off at $M_B^{cut} = -17.5$ mag [*i.e.* the Schechter (1976) function was multiplied by $exp(-10^{0.4(M-M^{cut})})$]. To convert the observed B-band LD's to the I-band, we adopted the following mean colors (Windhorst *et al.* 1994b) at z=0: $(B-I)_{E/S0} \simeq 2.3$, $(B-I)_{Sabc} \simeq 1.9$, and $(B-I)_{Sd/Irr} \simeq 1.4$ mag. The LF models were normalized to the observed number counts for all types at $m_{b_J} \simeq 18 - 20$ mag (c.f. KK92), resulting in a uniform 0.3 dex increase in numbers for each type. As discussed in DWG, this discrepancy in normalization arises from the observed steep galaxy counts at $b_J \lesssim 17$ mag (see also Shanks *et al.* 1989). In line with standard practise (c.f., KK92), we normalize our models, intended to represent a sufficient distance to cover a homogeneous volume (i.e., $z \sim 0.15$ or $b_J \sim 18 - 20$ mag), but at a low enough redshift that strong evolution has not yet occurred.

Figure 2b and 2c show the model predictions for ellipticals and early-type spirals, compared to our HST data. The models mimic the observed distribution rather well, implying — with the adopted LF normalization — little luminosity evolution (LE) for both the elliptical and early-type spiral populations. Note that the lightly dotted line on Figures 2b and 2c represent the predictions from the *un*normalized local LF's, which would imply stronger evolution for the early type populations. To model the late-type/Irregular population, three alternate LF's were used in the following four models:

(a) a *no-evolution* prediction based on the Loveday *et al.* (1992, LPEM) LD for late-type galaxies ($M_B^* = -18.5$ mag, $\alpha = -1.1$, $\phi_*(Sd/Irr) = 7.0 \times 10^{-4}$Mpc^{-3}, c.f. DWG).

(b) a *no-evolution* prediction based on the MGHC-LD for late-type galaxies ($M_B^* = -20.3$ mag, $\alpha = -1.5$, $\phi_* = 2.5 \times 10^{-4}$, DWG).

(c) an *evolving* model (Phillipps & Driver 1995) that mimics a ubiquitous starburst in the Sd/Irr galaxy population at z $\simeq$ 0.5, after which their luminosity declines exponentially with time (*i.e.* $\Delta m \propto \beta[1-(1+z)^{-\frac{3}{2}}]$ for $\Omega = 1$ with M_B^*, α, and $\phi_*(Sd/Irr)$ from (a) or (b), and β =free).

(d) a *no-evolution* dwarf-rich model with $\alpha = -1.8$, (c.f. Driver *et al.* 1994). The normalization is *increased* until a fit is found to the data ($M_B^* = -18.0$ mag, $\alpha = -1.8$, and $\phi_*(Sd/Irr) =$ free).

For models (a) and (b), the late-type/Irregular parameters listed above were taken *directly* from DWG. Figure 2d shows that they grossly under-predict the observed late-type/Irregular population. For model (c), the amount of luminosity evolution (LE) required for the *entire* late-type population was found to be $\Delta m \sim 2.0$ mag at z $\simeq$ 0.5 to match the counts with the LPEM-LF, and $\sim$ 1.3 mag with the MGHC-LF. The required $\sim$ 1.3 mag increase in luminosity for the *entire* late-type galaxy population is equivalent to a $\sim$ 2.0 mag increase in $\sim$ 20% of the population. For the dwarf-rich model (d), a local normalization of $\phi_* \sim 3.5 \times 10^{-2}\ Mpc^{-3}$ was required to match the counts, which is a factor of 5 greater than that of LPEM (not including the additional 0.3 dex normalization). Such a dwarf-LF, however, is inconsistent with the faint redshift surveys, as it predicts too many low-redshift objects (Driver 1994; Phillipps & Driver 1995).

Figure 3a (Color Plate 2) compares the best-fit individual LF's adopted for each galaxy type. Figure 3b shows the conventional differential number counts with the contribution from each galaxy type indicated by the best-fit model lines from Figs. 2a–2d. Fig. 3c shows the observed LD, which reflect the *actual* relative numbers that would be observed in a *magnitude-limited* survey (assuming equal selection effects for all types). Fig. 3d shows the *normalized* differential galaxy number counts which emphasizes the differences between the models and the data.

5 DISCUSSION AND CONCLUSIONS

Our observed differential HST counts for ellipticals (E/S0's) and early-type spirals (Sabc's) agree with the simple *no-evolution* model shown here, assuming the LF normalization is correct. Our

faintest HST counts lie at best marginally above the model predictions. This is consistent with a mildly evolving "giant" galaxy population undergoing a normal rate of star-formation (e.g. Bruzual & Charlot 1993). As a caveat to the above we note that the models described here have been normalized at $b_J = 18.0$ mag. Without this normalization, evolution *is* required in the luminous populations to explain the $\sim$0.3 dex difference between the models and our data. The fact that both populations require the same normalization and that the shape of the observed distribution matches the shape of the models rather well perhaps argues for the case to normalize. *However, until the local predictions of faint galaxy models are reconciled with the local redshift surveys, moderate (local) evolution in the giant galaxy populations cannot be ruled out.* Even so, an agreement within 0.3 dex places the end of the *major* star-formation epoch for these types to $z \gtrsim 0.8$, which is consistent with the lack of scale-length evolution observed in HST ellipticals out to z=0.8 (Mutz *et al.* 1994).

The late-type/Irregular population shows a considerable discrepancy between the no-evolution predictions and our deep HST data. This was also noted by DWG and GL95a down to I$\leq$22.0 mag, and has now been confirmed down to $m_I \sim 24.25$ mag with a steeply rising — almost Euclidean — slope and *no* indication for a turnover. The *no-evolution* models based on either the LPEM or MGHC LF's fall short of our deep HST observations by up to a factor 10 at the faintest limits. This late-type population is therefore clearly responsible for the "faint blue galaxy excess". Two possible solutions to this discrepancy are: strong evolution and/or a serious underestimation of the local space density of dwarf galaxies. The possibility of large-scale non-homogeneity or a gross error in the cosmological model is ruled out, as the E/S0 and Sabc models fit reasonably well to our HST data given our basic assumptions. While either of the possibilities considered here can be forced to fit our data, the implications are somewhat unpalatable.[2] If we evolve the widely adopted LPEM-LF, then $\sim$2.0 mag of brightening would be required at $z \sim 0.5$ in the *entire* dwarf galaxy population! Alternatively, the additional dwarfs required to explain this population without any evolution result in a significant low-redshift excess in the faint galaxy redshift distributions, which is not observed (GL95a), although the statistics in the redshift surveys are still small and the selection effects formidable. The more recent MGHC-LF — based on Zwicky magnitudes — offers a compromise: if the observed steep faint-end LF slope undergoes luminosity evolution, a more

[2] Note that again *if* normalization of the faint galaxy models at $b_J = 18$ mag is ignored the problem is amplified by another 0.3 dex.

reasonable value of ~ 1.3 mag brightening is implied at $z \sim 0.5$, equivalent to ~ 2.0 mag in ~20% of the population. The WFPC2 morphological surveys of DWG and GL95a concur that ~40% of the late-type/Irregular population shows evidence for recent star-formation, while the remaining galaxies appear inert. Together with our deeper HST counts, this leads us to conclude that the observed faint blue galaxy excess is caused by a combination of *strong evolution* in a *substantial fraction* of the late-type galaxy population *coupled with* an *under-representation* of late-type dwarf galaxies in local surveys (c.f. Driver & Phillipps 1995). This "family" of faint galaxy models is explored in detail in Phillipps & Driver (1995).

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TABLES

Table 1: Agreement between the four independent eyeball classifiers as function of flux.

Agree	Magnitude Interval		
-ment	$I < 20.25$	$20.25 < I < 22.25$	$22.25 < I < 24.25$
4 of 4	9 (75%)	12 (36%)	53 (36%)
3 of 4	3 (25%)	12 (36%)	54 (37%)
2 of 4	0 (0%)	9 (28%)	39 (27%)

Table 2: Comparison of the morphological mix of field galaxies by various groups.

Source	magnitude	E/S0	Sabc	Sd/Irr	Uncl.
MGHC (CFA1)[1]	$m_Z < 14.5$	35%	54%	10%	1%
MGHC (CFA2)[1]	$m_Z < 15.5$	42%	48%	8%	2%
Shanks *et al.* (1984)	$m_{b_J} < 16.0$	43%	45%	12%	0%
Griffiths *et al.* (1994)	$m_I < 22.25$	19%	44%	13%	25[2]%
DWG bright	$m_I \sim 20.25$	36%	50%	14%	0%
GL95a bright	$m_I = 20.25$	31%	48%	21%	0%
DWG faint	$m_I \sim 21.75$	28%	35%	31%	6%
GL95a faint	$m_I = 21.75$	29%	35%	33%	3%
Current, bright, Eye	$m_I \sim 22.00$	32%	38%	30%	0%
Current, bright, Auto[3]	$m_I \sim 22.00$	30%	70%		0%
	70%	0%			
Current, faint, Eye	$m_I \sim 24.00$	14%	30%	56%	0%
Current, faint, Auto[3]	$m_I \sim 24.00$	21%	79%		0%
$\longleftarrow$	79%	0%			
75%		0%			

Notes: [1] The mix for the CFA1 and CFA2 samples were estimated from Figure 1 of MGHC.
[2] Griffiths *et al.* (1994) note that a significant fraction of the unclassified galaxies were classified as S0 by one of their two classifiers.
[3] Automated classifications were determined from the profile fits of CRGINOW and Ratnatunga *et al.* (1995). This algorithm cannot distinguish between Sabc's and Sd/Irr's, so *all* disk dominated galaxies are listed together.

FIGURE CAPTIONS

Figure 1, COLOR PLATE 1 — This color image shows the 5.7 hr WFPC2 images in both the I_{814} and the V_{606} filters surrounding the weak radio galaxy 53W002 at z=2.390 (Windhorst & Keel 1995). Images in V, $(V+I)/2$ and I are shown in the blue, green and red guns respectively. A total of 600 objects in the I and 850 objects in the V frames have been detected down to $m_I \simeq 25.5$ and $m_V \simeq 26.75$ mag in 0.00136 deg^2, implying a surface density of 4.4×10^5 and 6.2×10^5 deg^{-2} in I and V, respectively. The V and I images have a 6.73^o difference in HST roll angle, leading to apparently extreme object colors at the CCD-edges.

Figure 2 — The differential I-band number counts for: (a) all galaxies; (b) ellipticals; (c) early-type spirals; and (d) late-type spirals/Irregulars. The open symbols without errorbars are from the larger but shallower HST surveys of CRGINOW (small symbols) and DWG (large symbols). The solid symbols with errorbars represent our new HST WFPC2 data. The errors are $\sqrt{n/N}$, where n represents number of objects and N the number of classifiers. The vertical *dotted* lines represent the range of agreement between classifiers, and is a conservative upper limit to the true errors. The lightly dotted lines on Fig. 2 b and c represent the *un*-normalized LF predictions (see text).

Figure 3, COLOR PLATE 2 — **(a)** The I-band luminosity functions (LF's) used in the morphological modelling. Three variants are shown for the late-type spiral/Irregular population: Loveday *et al.* (1992); Marzke *et al.* (1994b), and Driver *et al.* (1994a). **(b)** The resulting differential I-band number counts, along with the best fit models for each type (blue solid = dwarf-rich case, blue dashed = evolving Marzke-LF), as derived from Fig. 2a–2d. **(c)** As Fig. 3a, except that the LF's are displayed as they would be observed in a *magnitude-limited* sample. **(d)** The combined *normalized* differential galaxy counts for *all* galaxy types, and for ellipticals, early and late-type spirals based on our HST images. Also shown are the "shallower" data of CRGINOW and DWG, as well as the best fit models of Fig. 2a–2d. Note the similarity in shape between the luminosity distributions of the three major galaxy types in Fig. 3c and their *normalized* differential galaxy counts in Fig. 3d.